The Stars: their structure and evolution

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Introduction

This book is concerned with the structure and evolution of the stars, that is the life history of the stars. Its aim is to show how observations of the properties of stars and knowledge from many branches of physics have been combined, with the aid of the necessary mathematical techniques, to give us what we believe is a good understanding of the basis of this subject.

Because the stars are so remote from the Earth it may seem surprising that we can learn anything about their physical dimensions. To hope to be able to describe their internal structure and, still more, their evolution appears extremely optimistic. The mass and radius of a few stars can be measured directly, but for most stars the only source of information is in the light that we receive from them. This gives us some idea about the temperature and chemical composition of the *surface layers* of the star and about the total light output (*luminosity*) of those stars whose distance from the Earth is known. It also indicates that some stars are rotating rapidly or have strong magnetic fields and that others are losing mass from their surfaces. No direct information is obtained about physical conditions in the interiors of the stars, with the exceptions (discussed in Chapters 4 and 6) that the neutrinos emitted in the solar centre can be detected on Earth and that vibrations of the solar surface can provide information about the interior by techniques similar to seismology. The total of observational information which we have about the stars appears a small amount with which to hope to obtain an understanding of their internal structure.

If it seems presumptuous to hope to explain the present structure of stars, it is, perhaps, even worse when evolution is considered, for significant stellar evolution requires millions, or even thousands of millions, of years. Thus there are few instances of observation of stellar evolution and what there is can hardly be regarded as simple evolution. Some stars are observed to be losing mass into interstellar space, to be exchanging mass with a close companion or to be varying in their light output and occasionally a star explodes dramatically as a supernova, but there are no observations of changes in the properties of ordinary stars. For our nearest star, the Sun, there is no need of very detailed arguments to show that significant evolution must be very slow indeed. A small change in the Sun's properties would suffice to make the Earth uninhabitable for man, and man has been on Earth for hundreds of thousands, if not millions, of years. In fact, geologists say that the Earth's crust must have been solid for several thousand million years and that the Sun's luminosity cannot have changed significantly during that time. This gives an idea of the sort of time which is involved when we interest ourselves in the evolution of the Sun. I shall explain later that it is believed that more massive stars do evolve more rapidly, but even then we are usually concerned with periods of over a million years.

How then, is progress in this subject possible ? The main factor is that physics is a *relatively* simple subject with only a small number of fundamental laws. First, in the case of the structure of a star, we must be concerned with the forces which maintain it in equilibrium. At present it is believed that there are only four basic forces in nature (gravitational, electromagnetic, strong nuclear and weak nuclear) and only these can be involved in the structure of stars. The nuclear forces have a very short range and are not effective in holding together large bodies. The overall structure of a star is governed by the attractive force of gravity which pulls the star together and which is resisted by the thermal pressure of the material forming the star.

The main observational fact about stars is that they continuously radiate energy into space. This energy must have been released from some other source and have been transported from its point of release to the stellar surface. Perhaps the simplest idea would be to suppose that stars were created as very hot bodies and have been cooling down gradually ever since, but I shall show in Chapter 3 that it is impossible to reconcile this with the Sun's steady luminosity for such a long time. If this idea is discarded, the energy must have been converted into heat energy from another form inside the star, and it is then necessary to consider whether gravitational energy, chemical energy or nuclear energy might be involved. When the problem of the Sun's energy supply is considered in detail in Chapter 3, it becomes clear that only nuclear energy can meet the requirements and, in fact, essentially only one process, the conversion of hydrogen into helium with release of nuclear binding energy, can do it.

Of course, these facts that seem so obvious today were not always so clear. The structure and evolution of the stars were being studied before the properties of nuclear binding energy were fully understood and it was then thought that there must be a new unknown source of energy such as, perhaps, the *complete* annihilation of matter into radiation. At one time it was thought that the centres of stars were not hot enough for significant nuclear reactions to occur, and at this time Eddington made his famous suggestion that, if the centres of the stars were not hot enough, the nuclear physicists should look for a hotter place. I shall explain in Chapter 4 that the development of the quantum theory made this search unnecessary.

Although the basic forces of nature are few, the calculation of the structure of a star is not simple, as there are so many detailed physical processes which must be considered. It is necessary to have expressions for the rates of many nuclear reactions involved in the release of nuclear energy and even the conversion of hydrogen into helium involves several successive reactions. The energy released by the nuclear reactions must be carried from its point of release to the surface where it is radiated. I must therefore discuss whether the energy is carried principally by conduction, convection or radiation and must study the detailed processes involved in this transport of energy. As mentioned earlier, the pressure of the stellar material resists the attractive gravitational force tending to make a star smaller and the thermodynamic state of the stellar material must be studied so as to discover how pressure depends on temperature and density. In the discussion of the origin and transport of radiation and of the pressure of the stellar material, results will depend on the chemical composition of the star. Some information can be obtained about the chemical composition of the outer layers of a star from the occurrence of an element's characteristic spectral lines in the star's radiation, but it must be recognised that this might not be representative of the chemical composition of the star as a whole.

Because he has only limited information about the properties of *actual* stars, the theoretical astrophysicist tends to calculate the structure of a wide range of *possible* stars rather than trying to explain the properties of an individual star. According to the present theoretical ideas, a few basic properties of a star essentially determine its structure and evolution. The most important factors are believed to be mass and chemical composition, and calculations are made for a variety of different values for these. It then proves more useful to ask whether theory predicts a correct relationship between the properties of stars of different mass and chemical composition rather than whether it predicts the properties of an individual star, which are known only approximately. As I shall explain in the following paragraph, this procedure has been particularly useful because there are important regularities in the observed properties of stars. The only exception to this treatment of stars statistically rather then individually is that the Sun has received very detailed attention because we have so much information about it.

A major stimulus to the study of the evolution of the stars comes from the fact that, if one studies the value of mass, radius, luminosity and surface temperature for those stars for which values are available, it is found that not all combinations of values of these quantities are equally probable. The radius, luminosity and surface temperature are not independent because the energy radiated by unit area of the surface of a star is essentially determined by how hot it is. If I regard mass, luminosity and surface temperature as three independent quantities I can draw two independent diagrams relating them. It is usual to plot mass against luminosity (fig. 1) and luminosity against surface temperature (fig. 2) and in both of these diagrams most stars lie in quite narrow bands and there are large regions of the diagrams which contain no stars. For example, it is found that on the average the more massive stars are more luminous and have higher surface temperatures than less massive stars. One of the first tasks of stellar structure theory it to try to explain this regularity and it seems possible that there might be a reasonably simple explanation.

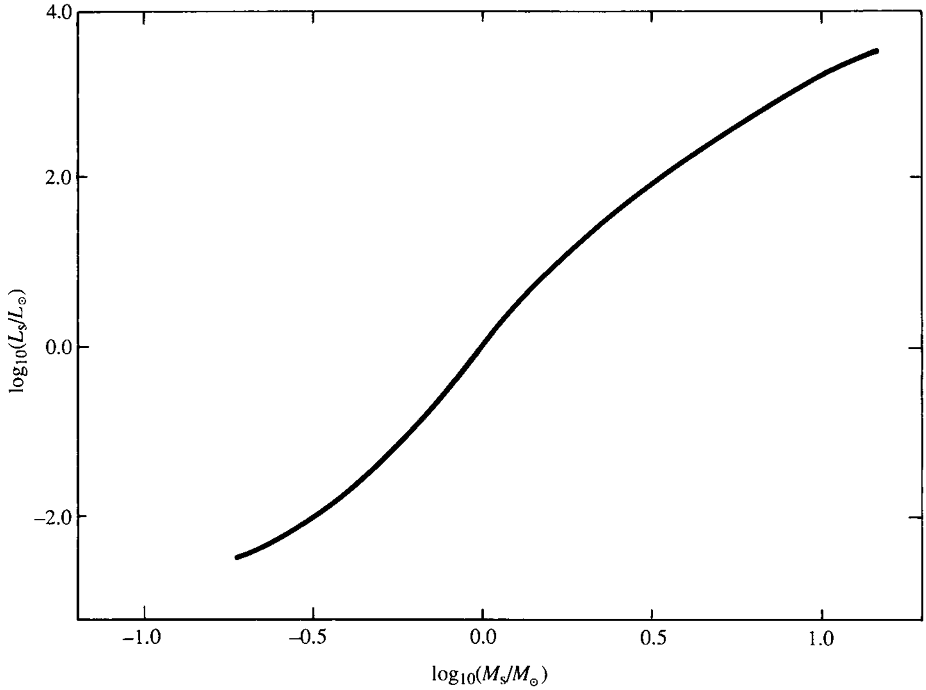

Fig. 1. The mass–luminosity relation. The luminosity L_s is plotted against the mass M_s. $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun. Stars with accurately known luminosity and mass lie close to the curve shown, provided that they are main sequence stars (see Fig. 2).

It is believed that the three main factors determining the properties of a star are its *mass*, its *chemical composition* (when it is formed) and its *age*. Our observations of stars are complicated by their varying distances and the fact that obscuring matter produces an interstellar fog of varying density between us and the stars. Any attempt to interpret the properties of the whole group of stars for which there are good observational details is also complicated by the fact that the stars vary in mass, chemical composition and age. Such interpretation is easier for the groups of stars which are known as star clusters. These clusters of stars are apparently true physical groupings of stars rather than accidental concentrations, which happen to be in the same direction in the sky, but at very different distances. For a compact cluster it may be hypothesized that, of the five factors mentioned above which contribute to the appearance of a star, four, initial chemical composition, age, distance of the star from the Earth and the obscuring matter in the line of sight, might vary only slightly from star to star. If this is true, *the main factor which accounts for the differences in the observed properties of the stars is that they have different masses*. This has been the basis of most work on stellar evolution to date and it will be discussed in Chapter 6. Clearly, all of the five quantites do vary from star to star, but it seems reasonable that the variation of mass is most important.

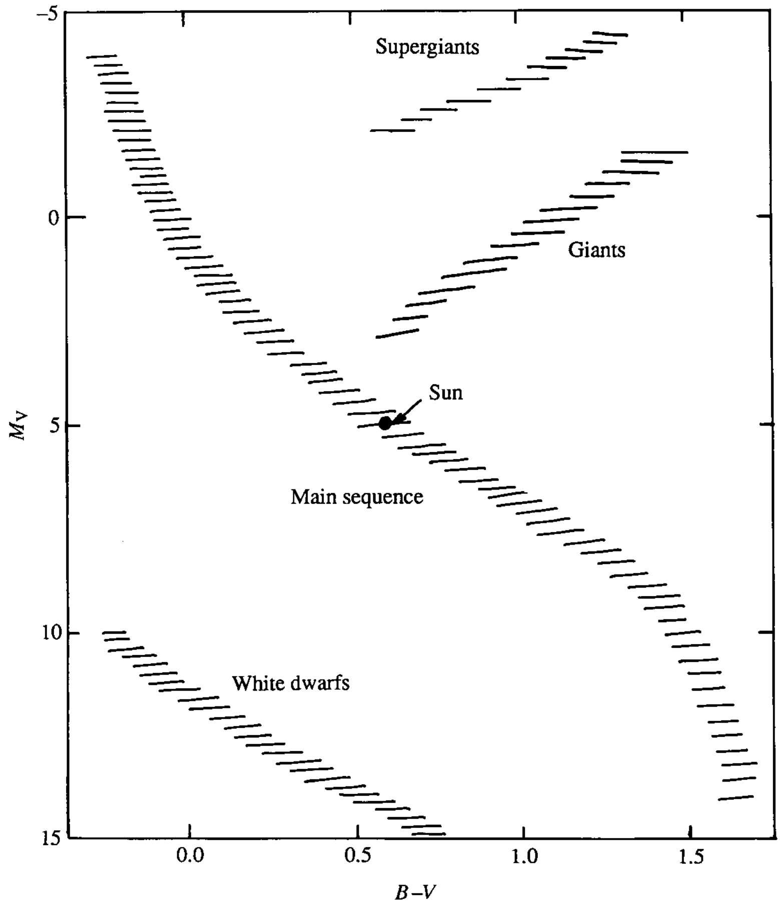

Fig. 2. The Hertzsprung–Russell diagram for nearby stars. The visual magnitude M_V is plotted against colour index B–V and most stars fall in four well-defined groups. (M_V is proportional to $-\log L_S$ and B–V is related to surface temperature, as shown in Table 1, page 17).

I have already mentioned that the Sun's properties are changing very slowly at present and it is further believed that slow variation of observational properties is characteristic of that phase in a star's evolution when nuclear reactions converting hydrogen into helium are occurring in the star's interior and are providing the energy that the star is radiating. This slow evolution prevents us from observing the rate at which stellar properties change, but it also has a very useful consequence in the theory of stellar structure. Because the hydrogen burning phase takes so long, the star settles down in a state which is almost independent of its previous history. This is useful because even now there is no very good theory of how stars are formed. If the study of stellar structure and evolution depended on having a comprehensive theory of star formation, the subject would have been much slower getting under way. Luckily it has been possible to regard the hydrogen burning phase of stellar evolution as the first stage.

Although the basic physical processes involved in stars, such as those concerned with energy release and energy transport, have been known since the 1930s and calculations of stellar structure had already been made even before all of the physical processes were understood, most of detailed work on stellar evolution has been done since 1960. This is largely because, when all of the physics of stellar interiors is to be taken into account, the equations of stellar structure and evolution can only be solved with the aid of a large computer and such computers did not become available until then. The advent of the large fast computer has revolutionized the amount of detail which can be included in the studies, although even now it is difficult to study very rapid stages of evolution particularly of non-spherical stars. This does not mean that there is no scope for less detailed calculations in which approximate values are used for some of the physical quantities in order to make the equations more tractable. In fact, as I shall discuss in Chapter 5, the general trends of luminosity and surface temperature as a function of mass can be understood on the basis of simplified physical laws. However, any detailed comparison between theory and observation requires the use of the most accurate mathematical expressions for physical laws.

It should be stressed that this is a book on a developing subject and that it is not an account of a field in which everything is understood. There are still some serious gaps in our knowledge and it has been my aim to mention and underline these rather than to pretend that they do not exist. Nevertheless I do feel that there is a good general understanding of the subject and believe, perhaps wrongly, that future changes will be ones of detail rather than upsets in the broad principles of the subject.

It is also hoped that what follows in the book will give some idea of how a research scientist approaches a problem. When a subject is completed it may be possible to present its development in a completely logical manner in which each step follows smoothly from the previous one. This is not, however, the situation when a subject is developing. Then it is more like working on a jigsaw puzzle. Pieces must be tried tentatively; the consequences of a variety of assumptions must be tried out. Parts of the subject may be studied in isolation in the hope that, when the whole pattern of the subject emerges, they will fit neatly into it. This is very much the situation with some parts of the subject of this book, particularly the contents of Chapters 7–10.

It should be clear from what has been said earlier that the study of stellar structure requires knowledge from many branches of physics such as atomic physics, nuclear physics, thermodynamics and gravitation. However, it should be stressed that the subject not only makes use of basic physical knowledge, but it also stimulates the development of further knowledge. In particular, I shall mention later that developments in nuclear physics have been stimulated by the need to understand the laws of energy release in stellar interiors and that study of final stages of evolution of massive stars is leading to interest in the behaviour of the law of gravitation in matter at extremely high densities. It should be remarked that the laws of physics as we understand them, have been obtained from experiments on the Earth and in its immediate environment. In studying the stars and the more distant parts of the Universe, *I make the assumption that the laws of physics are unchanging and are the same in all parts of the Universe*. This could be an incorrect assumption and, although I always try to understand astrophysical phenomena within the framework of existing physical laws, the possibility that this might be wrong must always be borne in mind.

Most of the book is concerned with the structure of isolated spherically symmetrical stars. This means, in particular, that mass loss from stars is largely ignored. In the past twenty years it has become apparent that mass loss is important at many stages of stellar evolution and that the final mass of a star may be very much less than its initial mass. In addition many of the more spectacular events in stellar evolution involve mass exchange between two stars which are close companions in a binary system. Thus departure from equilibrium and from spherical symmetry may be important in some stages of stellar evolution. At some stages in their evolution stars may suffer from instability which causes their properties to become variable. The detailed discussion of stellar stability and variable stars is too advanced for this book, but I shall explain the place in the evolutionary scheme of some of the important types of variable star.

I shall not discuss in any detail the importance of an understanding of stellar structure and evolution for astronomy in general. Stars are the most important component in the visible Universe and an understanding of galactic evolution requires a detailed knowledge of star formation, stellar evolution and mass loss from stars. Astronomers are now able to study galaxies at very large distances and hence in the remote past. The properties of such young galaxies are largely determined by the manner in which stars first formed in them.

The remainder of this book is arranged as follows. The observed properties of stars and the techniques of observation are described briefly in Chapter 2. The equations determining the structure of stars are discussed in Chapter 3. Included in these equations are quantities whose values can only be obtained by a rather detailed consideration of the physical state of stellar interiors, and the physics of stellar interiors is discussed in Chapter 4. The structure of hydrogen-burning stars at the beginning of their evolution, when nuclear reactions have just started to supply the energy the stars are radiating, is considered in Chapter 5. The chapter also contains a brief discussion of star formation and pre-main-sequence evolution. The early evolution of these stars is discussed in Chapter 6. Mass loss from stars is discussed in Chapter 7 and the properties of close binary stars in Chapter 8. Chapters 9 and 10 are concerned with later stages of stellar evolution. Finally, some of the problems for future study are described in Chapter 11.